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13. ABSTRACT (Maximum 200 words)

This study explored a novel higher strength and higher impact tolerant syntactic foam for composite sandwich structures. A unique microstructure was designed and realized through a unique manufacturing technology. The foam was fabricated by dispersing rubber latex coated microballoons into a nanoclay and milled microfiber reinforced epoxy matrix. Each component was designed to contribute to a desired property of the foam. The nanoparticle and microfiber served to increase the strength and stiffness (stronger and stiffener); the microballoon served as a light-weight filler (lighter); and the rubber coating served to increase the toughness and the impact tolerance (tougher). The manufacturing process for developing this unique microstructure was developed. Both low velocity impact test and four-point bending test were conducted on the foam core and sandwich beams. The test results showed a considerable increase in energy absorption capacity and the capacity for retaining the residual bending strength. This multi-phase material contained structures bridging over several length-scales. The SEM pictures showed that several mechanisms were activated to collaboratively absorb impact energy, including microballoon crushing, interfacial debonding, matrix cracking, rubber pinning, fiber pull-out, and fiber bridge-over. The localized and microscale damage insured that the sandwich beams retained its strength after the impact.

14. SUBJECT TERMS
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4. Statement of the problem studied

A core is the most crucial component in a composite sandwich structure. It takes care of separating and fixing the skins, carrying the transverse shear load, and providing other structural or functional duties such as impact resistance, radiation shielding, etc. In practice, various core materials have been used, such as foam core (balsa wood, polymeric foam, metallic foam, ceramic foam, syntactic foam, etc.) [1-9], web core (truss, honeycomb, corrugated, etc.) [10,11], 3-D integrated core [12,13], and foam filled web core (foam filled honeycomb and foam filled 3-D integrated core) [4]. Although the existing core materials have been very successful in carrying static and dynamic loads, there is a considerable room left for further improvement in enhancing the energy absorption capacity because a foreign object impact is becoming a major concern for most applications of composite sandwich structures. The purpose of this study is to develop a novel hybrid syntactic foam core for more effectively absorbing impact energy without significantly sacrificing strength.

5. Summary of the most important results

5.1 Microstructure design

Syntactic foam – a light weight material with polymeric, ceramic, or metallic microballoons dispersed in a polymer matrix, is becoming more and more accepted in impact tolerant sandwich structures. The underlying principle for absorbing impact energy is that the microballoons will be deformed and crushed, the microballoon/matrix interface will be debonded, and the matrix will be cracked. The crushing of the microballoons and the creation of new surfaces serve to consume a considerable amount of impact energy. In order to further enhance the energy absorption capacity, more energy absorbing mechanisms must be introduced so that damage in a small volume can absorb a significant amount of impact energy. Owing to the localized damage, it is expected that the effect of the damage to the structural capacity will be minimal, i.e., without significantly sacrificing strength.

In this study, a novel microstructure is proposed and developed. This foam has a carefully designed microstructure with rubber coated microballoons dispersed in a nanoparticle and microfiber reinforced polymer matrix. Each component is designed to contribute to a desired property of the foam. The nanoparticle and microfiber serve to increase the strength and stiffness; the microballoon serves to reduce the weight; and the rubber coating serves to absorb impact energy and blunt and arrest microcracks. This multi-phase material contains structures bridging over several length-scales, which would contribute to absorb and dissipate impact energy with minimal loss in strength.

5.2 Raw materials

A styrene–butadiene rubber (SBR) latex - Rovene 4040 with a density 1.0g/cm^3 and solid content 50% from Mallard Creek polymers, Q-cel 6048 glass microballoons with an average particle size of 50 μm and a specific density 0.48g/cm^3 from Potters Industries Incorporation, nanoclay I.28E with an average particle thickness 1nm, length of 100-400nm, and density 1.73g/cm^3 from Nanocor corporation, milled glass fibers with a length 1.6mm, diameter 15.8 μm, and density 2.5g/cm^3 from Fiberglast Developments Corporation, DER 332 epoxy cured with a DEH 24 curing agent, both with a density 1.06g/cm^3 from DOW Chemicals, and Plain woven 7715 style fabric with a density 2.54g/cm^3 from Fiberglast were selected to develop the syntactic foam and the sandwich beam.

5.3 Foam Fabrication and Specimens Preparation

In order to create the designed microstructure, the procedure for fabricating the foam material started with coating the microballoons using the rubber latex while stirring and heating until most of the water was removed. Before the mixing, a coupling agent, a methanol diluted silane (in a ratio of 85:15 by weight) was used to surface treat the microballoons to enhance the interfacial bonding strength between the microballoons and the rubber. Figure 1 shows the microballoon/rubber latex mixture at the very beginning of the mixing process and Figure 2 shows the mixture near the end of the mixing process. The nanoparticles were mixed with DER 332 using the Sonic V750 ultrasonic mixer until uniformity. Figure 3 shows the set-up of the mixing system. The mixing took 20 minutes at 40% of the maximum amplitude. After that, microfibers were added to the nanoclay/DER 332 mixture while stirring. Figure 4 shows mixing the microfibers. The curing agent DEH 24 was then added to the nanoclay/DER332/microfiber mixture followed by adding the rubber coated microballoons while stirring. Mixing was conducted continuously until uniformity. Figure 5 shows mixing the system. The mixture was then poured into an aluminum mold for curing at a room temperature for 12 hours and post curing at 150^{o}F for 12 hours, 250^{o}F for 2 hours, and 350^{o}F for 30 minutes. This procedure helps in fully curing the foam and removing the entrapped water. Once the molded slab was cured, it was cut into 304.8mm long, 50.8mm wide, and 15.2mm thick beam specimens. Figure 6 shows cutting the specimens with a band saw. A total of six groups of specimens were prepared. Each group contained 12 identical specimens. The total number of specimens was 72. The volume fraction of each group is given in Table 1. Six specimens from each group were wrapped using two layers of E-glass 7715 style plain woven fabric reinforced epoxy to fabricate sandwich beams. Figure 7 shows wrapping the fiber reinforced skin using the hand lay-up technology.

5.4 Experiment

Two types of tests were conducted. One was a low velocity impact test using the DynaTup 8250HV impactor with a hammer weight 3.4kg and a velocity 3m/s, and the other was a four-point bending test using the MTS 810 machine with a span length 254mm and a loading rate 4.1mm/min. Figure 8 shows the impactor and Figure 9 shows the MTS machine.

5.5 Impact test results

Figure 10 shows a typical load-time and energy-time curve of a Group 2 foam specimen; Figure 11 shows a typical load-time and energy-time response of a Group 4 sandwich beam specimen. The initiation energy and propagation energy of the pure core and sandwich specimens are given in Table 2 and 3, respectively.

Comparing the currently available foam, Group 1, with the rubberized foam, Groups 3-6, it is found that the initiation energy and propagation energy of the rubberized foam are higher; see Table 2. The increase in propagation energy suggests that the rubberized foams possess a higher capacity to absorb impact energy. The increase in initiation energy, on the other hand, suggests that the rubberized foams can also transfer more impact energy into elastic strain energy before the major and macroscopic damage occurs. Therefore, the rubberized foams can effectively dissipate the impact energy in the form of both energy transfer (in terms of initiation energy) and energy absorption (in terms of propagation energy). For the four groups of rubberized foams, it is found that Group 4 has the highest propagation energy, suggesting that it is the best composition in terms of energy absorption.

Comparing Group 2 with Group 1, it is found that the propagation energy of the Group 2 specimen is higher. This suggests that the addition of microfibers and nanoclay serves to increase the number of mechanisms for energy absorption such as the fiber pull-out mechanism.

Once the various types of foam materials are used as sandwich cores, the energy dissipation behavior alters when compared to the pure foam cores. In Table 3, the rubberized foam core sandwiches, Groups 3-6, have higher initiation energy and lower propagation energy than the Group 1 sandwich, which is the currently available sandwich. The increase in initiation energy suggests that as a sandwich core, the rubberized foams can transfer and store more impact energy into elastic strain energy before macroscopic damage occurs. Part of the initiation energy will be transferred back to the hammer and part will be dissipated by vibration and damping of the sandwich. The decrease in propagation energy means that less damage is created in the rubberized foam core sandwiches. The reduced damage should be translated into higher residual strength. This is exactly the case; see discussions in **Section 5.6**. For the four groups of sandwiches with rubberized cores, it is found that the Group 4 has the highest initiation energy and the least propagation energy.

For the Group 2 sandwich, it also shows a higher initiation energy and lower propagation energy than that of Group 1. This suggests that the addition of microfibers and nanaoclay serves to increase the strength of the sandwich.

While the pure rubberized foam cores show a higher propagation energy than that of the Group 1 foam, Table 2, the rubberized core sandwiches show a lower propagation energy than that of the Group 1 sandwich, Table 3. The reason for this is that the sandwich skin distributes the impact load to a larger area. Consequently, more core materials are activated to dissipate impact energy. Due to the existence of the highly elastic rubber, the rubberized cores store more elastic energy in the form of elastic strain energy, leaving a small amount of energy to create and propagate damage. As a result, the propagation energy is very small.

The reason for the better impact tolerance of rubberized foam can be understood from the microscopic observation. It is expected that the rubberized foam dissipates impact energy through elastic deformation of the rubber coating layer besides the crushing, interfacial debonding, matrix cracking, fiber pull-out, and fiber bridge-over mechanisms. Figure 12 and Figure 13 show the crushing of microballoons and interfacial debonding in a Group 1 specimen, respectively. An SEM picture in Fig. 14 shows the successful coating of a rubber layer on the surface of the microballoon. Figure 15 shows three energy absorbing mechanisms (microballoon crushing, interfacial debonding, and fiber pull-out) have been activated in a Group 4 specimen. It is interesting to note that the specially designed microstructure of the rubberized foams not only provides a way for absorbing energy through damage, but also provides mechanisms to contain micro-scale damage from propagating into catastrophic macrocracking. In Fig. 16, it is clearly seen that a microfiber bridges over the matrix cracking in a Group 4 specimen. Figure 17 shows the matrix cracking, one of the important mechanisms for absorbing impact energy, was blunted and contained by the rubber layer in a Group 5 specimen. Therefore, the idea proposed in this project is validated. The designed structure provides a way of absorbing impact energy without significantly reducing strength.

5.6 Bending test results

Typical load-deflection curves of the foam core and damaged and undamaged sandwich specimens from Group 6 are shown in Fig. 18. The peak bending loads of the foam core, sandwich, and sandwich after impact, are summarized in Table 4. No residual bending strength is available for the pure foam cores because they are significantly damaged and bending test cannot be conducted.

From Table 4, the sandwich construction significantly increases the bending strength of the foam core. Therefore, although the strength of the foams is very low, they are suitable for application to sandwich structures. After impact, the Group 1 sandwich, which uses the currently available syntactic foam core, shows the largest reduction in strength. This is in agreement with the impact test results that Group 1 sandwich has the highest propagation energy or the largest damage. For the rubberized core sandwiches, Groups 3-6, the reduction in strength is smaller than that in Group 1. The least reduction in strength is found in the Group 4 sandwich. Actually, the bending strength of the impact damaged sandwich beam is slightly higher than that of the undamaged beam. This can be understood in such a way that the impact damage is so small in the Group 4 sandwich beams that the effect is negligible statistically. It is also noted that all the rubberized foam sandwiches, except for the Group 3 which contains 5% rubber, have a higher residual bending strength than the Group 1 sandwich beams. Combined with their higher energy dissipation capacity, it is concluded that the developed foam cores have achieved the objective of the proposed study, i.e., higher impact tolerance with lower reduction in strength.

5.7 Conclusion

Based on the testing and characterization, it is concluded that the proposed rubberized foams has the highest energy dissipation capacity with the least sacrifice in strength. Therefore, the objective of this STIR project is achieved. In particular, the Group 4 foam, which has 10% rubber, shows the highest energy dissipation capacity and the least reduction in bending strength. It is the best candidate for in-depth studies.

Future studies will include, at a minimum, applying the developed foam to existing armor system and conducting theoretical modeling for optimized design of the foam and corresponding armor structures subjected to both low and high velocity impact loads.

6. List of publications

(b) Paper published/presented in conference proceedings

(1) Guoqiang Li**, “**Low velocity impact degradation, characterization, and rehabilitation of composite structures,” 14th international conference on composite/nanocomposite engineering, Boulder, Colorado, July 2-8, 2006.

(2) Nji Jones and Guoqiang Li, "Low velocity impact response of a hybrid syntactic foam," 14th international conference on composite/nanocomposite engineering, Boulder, Colorado, July 2-8, 2006.
(3) Venkata D. Muthyala and Guoqiang Li, "A cement based syntactic foam," 14th international conference on composite/nanocomposite engineering, Boulder, Colorado, July 2-8, 2006.
(4) Manu John and Guoqiang Li, "A rubberized nanocomposite foam core," 14th international conference on composite/nanocomposite engineering, Boulder, Colorado, July 2-8, 2006.
(5) Guoqiang Li, Jinquan Cheng, and Su-Seng Pang, "Experimental study of composite sandwich structures with a grid stiffened hybrid core," 14th international conference on composite/nanocomposite engineering, Boulder, Colorado, July 2-8, 2006.

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10. Appendix

Table 1 Volume fraction of constituents in each group (%)

Group No.	1	2	3	4	5	6
Epoxy	40	40	40	40	40	40
Rubber	-	-	5	10	15	20
Microballoon	60	55	50	45	40	35
Nanoclay	-	2.5	2.5	2.5	2.5	2.5
Microfiber	-	2.5	2.5	2.5	2.5	2.5

Table 2 Impact test results of pure core

Group No.	1	2	3	4	5	6
Initiation energy (J)	1.4	1.2	1.1	2.7	3.0	2.8
Propagation energy (J)	4.0	7.2	7.3	9.0	5.8	5.7

Table 3 Impact test results of sandwiches

Group No.	1	2	3	4	5	6
Initiation energy (J)	7.1	8.9	9.6	13.3	11.8	11.7
Propagation energy (J)	6.1	4.8	4.6	0.6	1.7	1.9

Table 4 Peak bending load (N)

Group No.	Pure foam core	Sandwich	Impacted sandwich
1	500	4842	3947
2	450	4940	4728
3	298	4151	3853
4	280	4529	4555
5	311	5952	5600
6	306	5692	5285

Fig. 1 Mixing rubber latex and microballoons (at the very beginning of the mixing process)

Fig. 2 Mixing rubber latex with microballoons (near the end of the mixing process)

Fig. 3 Mixing nanoclay using the ultrasound mixer

Fig. 4 Mixing microfibers

Fig. 5 Mixing the foam mixture

Fig. 6 Cutting beam specimens

Fig. 7 Wrapping sandwich skin

Fig. 8 DynaTup 8250 HV impactor

Fig. 9 A sandwich specimen under four-point bending test

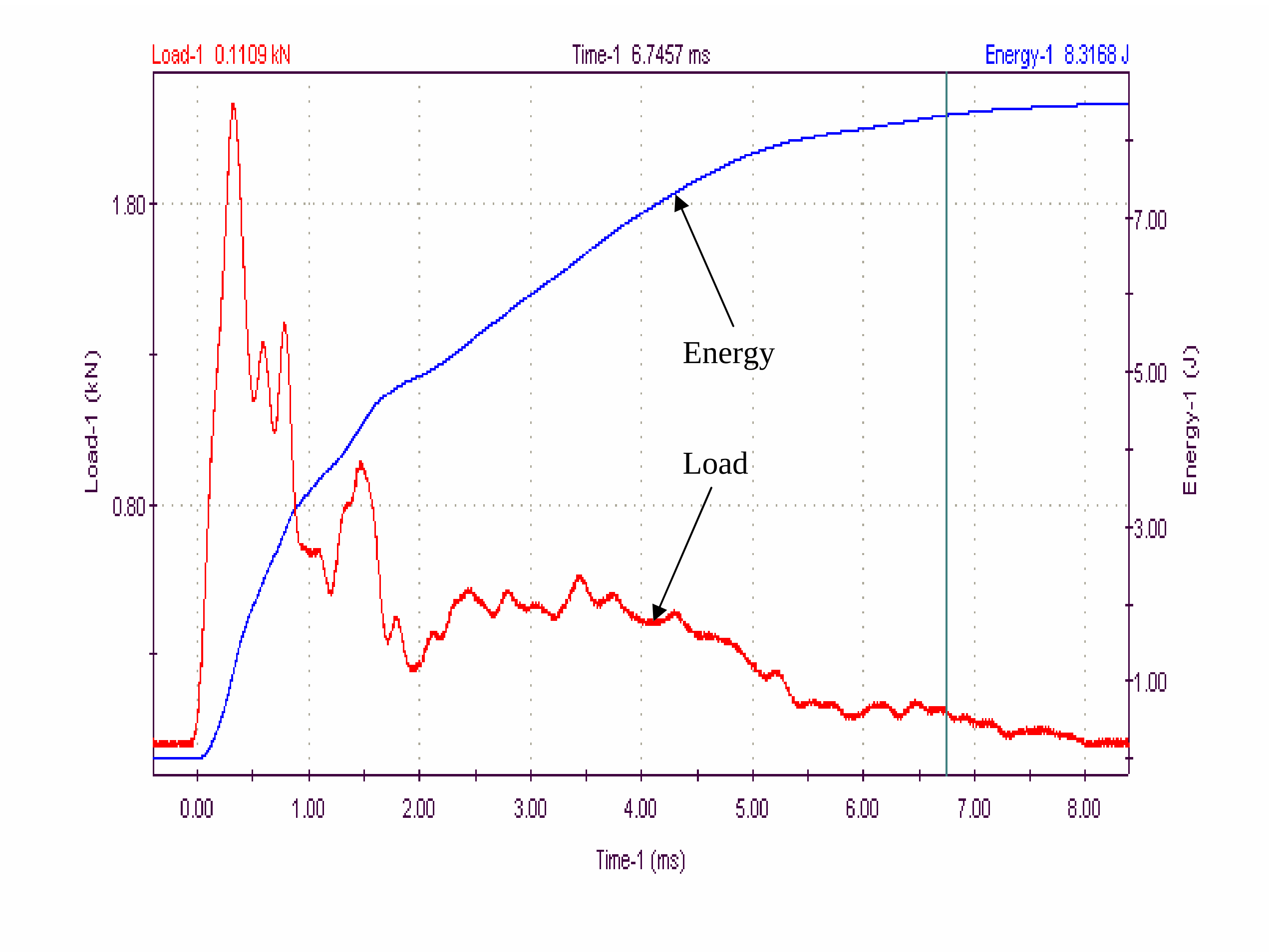

Fig. 10 A typical impact test result of a Group 2 foam specimen

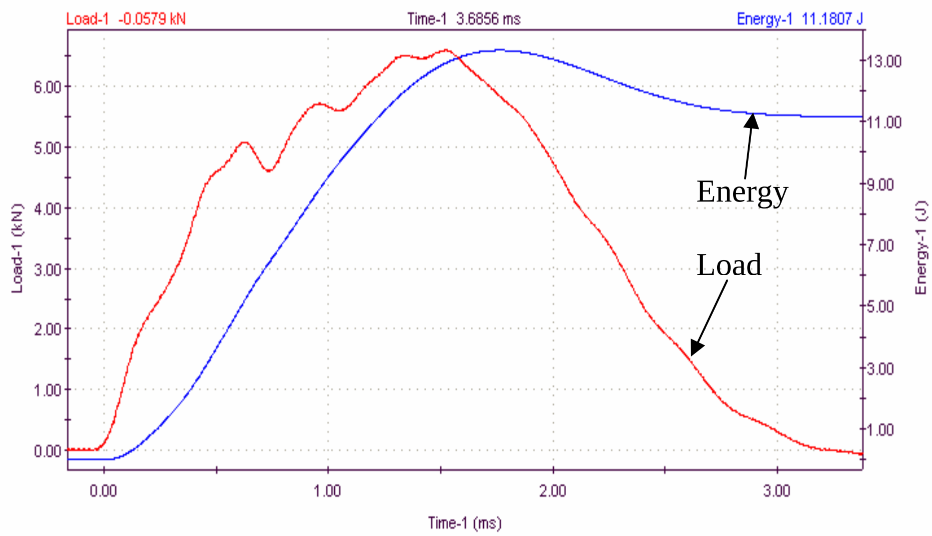

Fig. 11 A typical impact test result of a Group 4 sandwich beam specimen

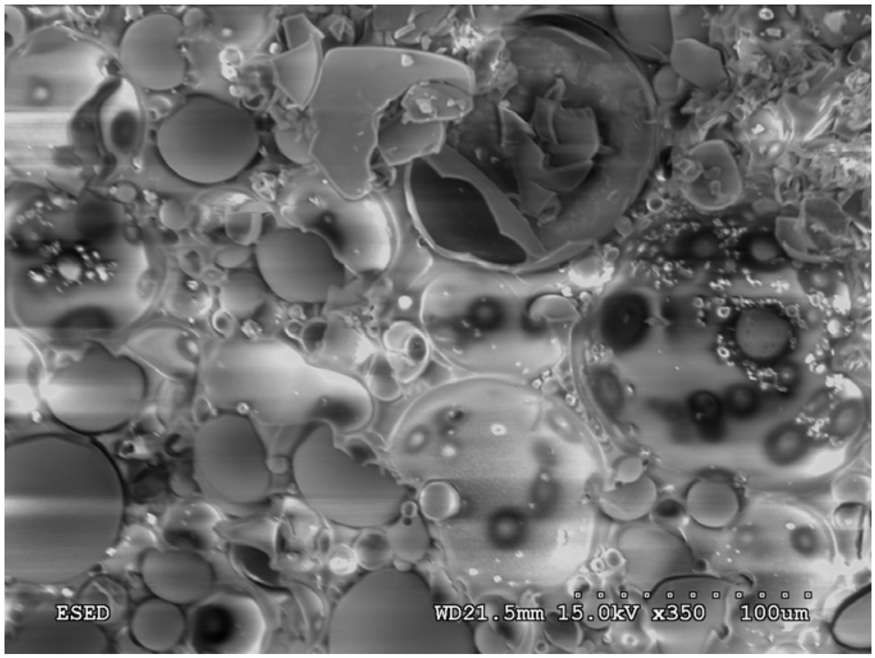

Fig. 12 Microballoon crushing in a Group 1 foam specimen

Fig. 13 Interfacial debonding in a Group 1 foam specimen

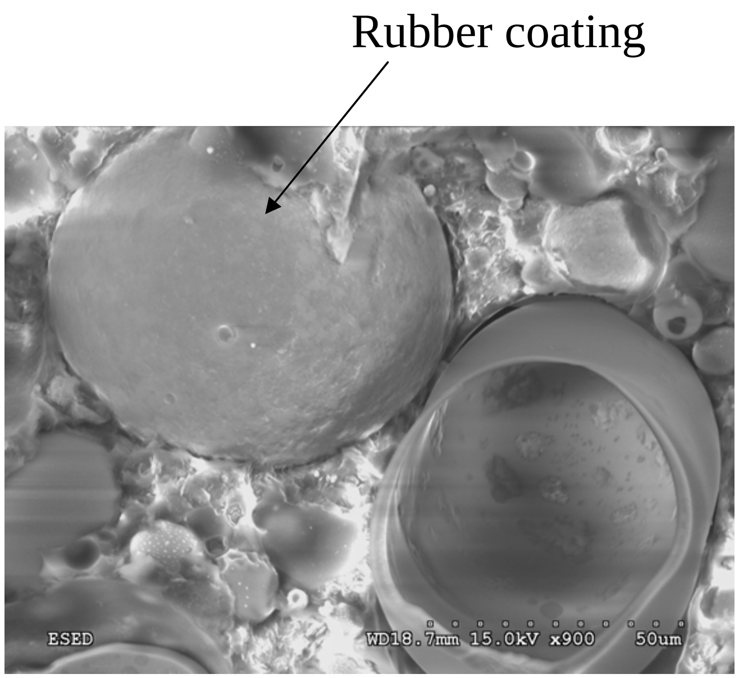

Fig. 14 Rubber coating on the surface of the microballoon (Group 4 foam)

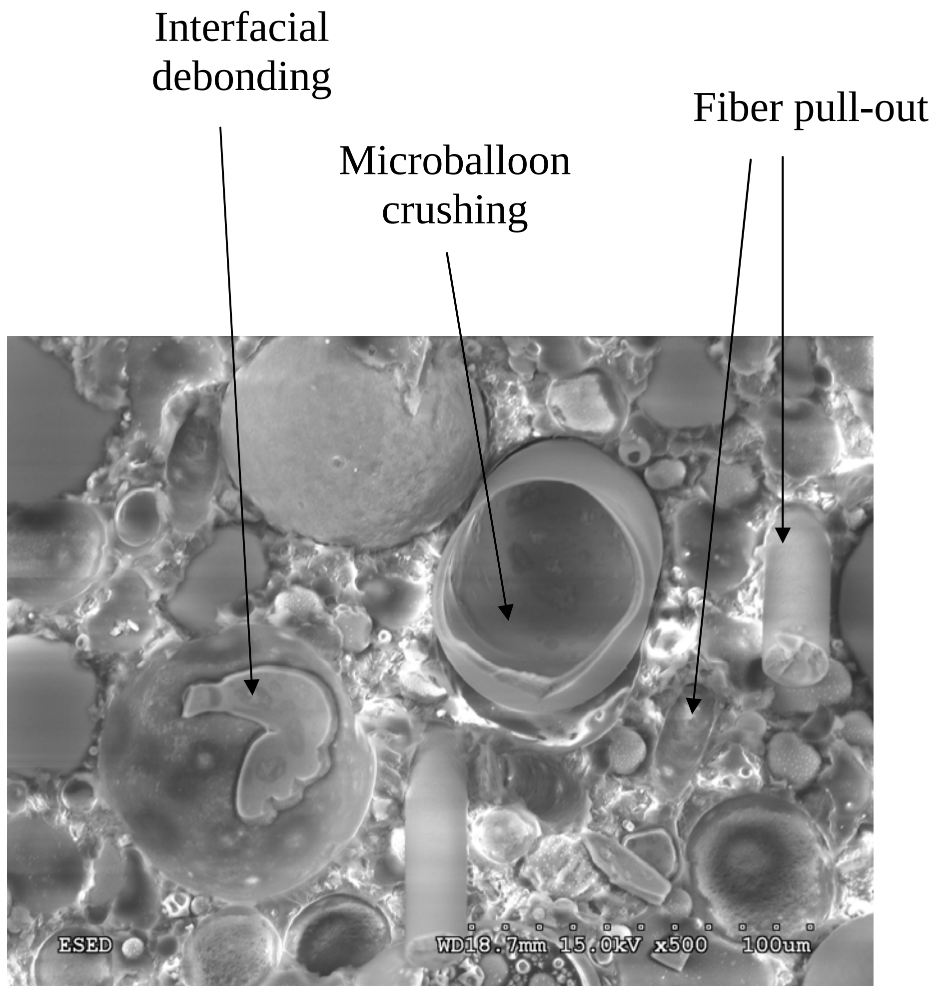

Fig. 15 Microballoon crushing, interfacial debonding, and fiber pull-out (Group 4 foam)

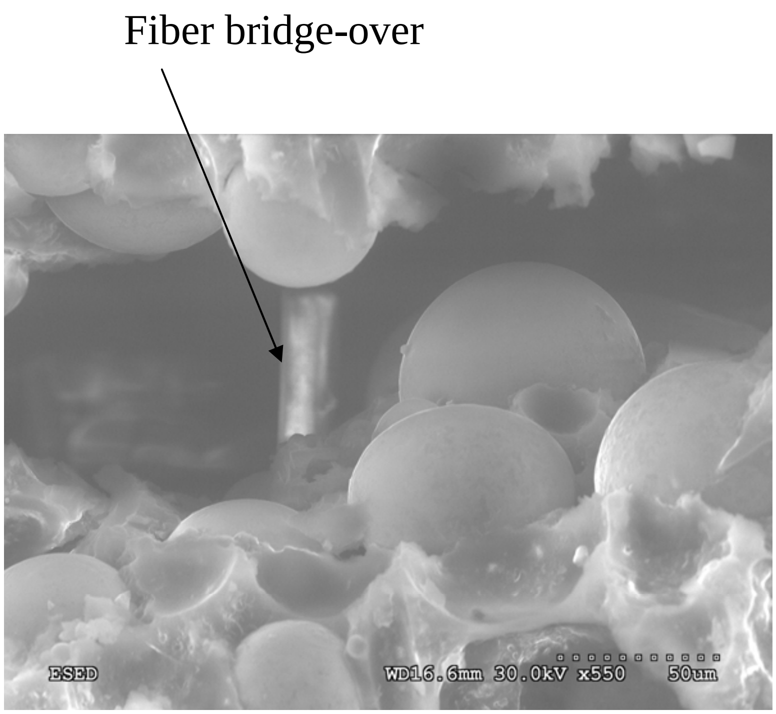

Fig. 16 Fiber bridge-over in a Group 4 foam specimen

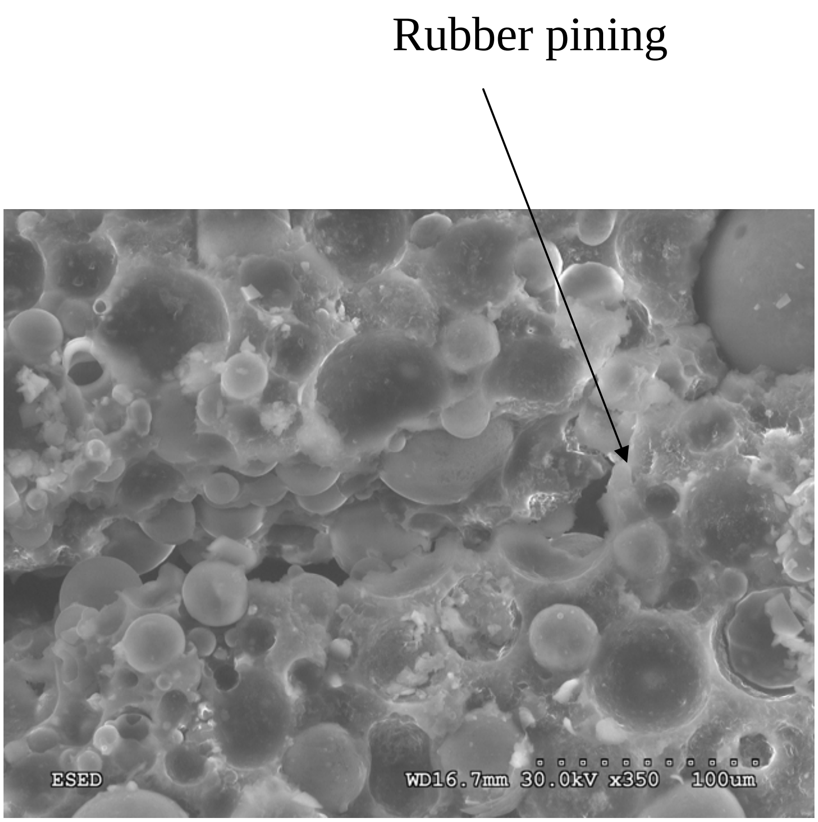

Fig. 17 Rubber pining of matrix cracking in a Group 5 foam specimen

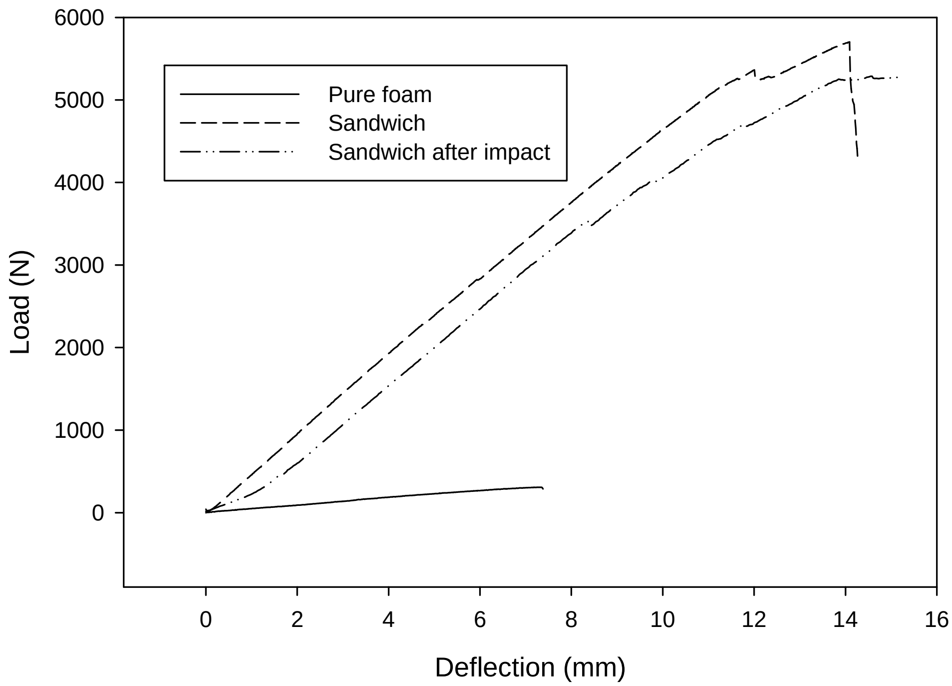

Fig. 18 Load-deflection curves of Group 6 specimens

LOW VELOCITY IMPACT DEGRADATION, CHARACTERIZATION, AND REHABILITATION OF COMPOSITE STRUCTURES

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Introduction

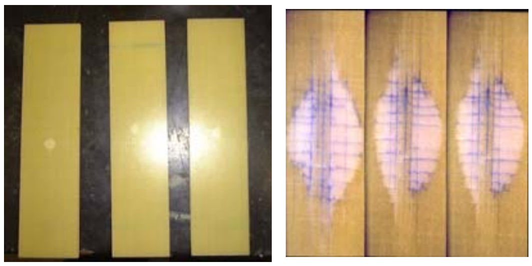
Fiber reinforced polymer composites in the form of laminate, sandwich, grid, and hybrid structures have been widely used in various civilian and military structures and equipment due to their high specific strength/stiffness, corrosion resistance, and tailorability. In addition to carrying the designed static/dynamic loads, most composite structures experience some kinds of low or high velocity impact incidents during their life cycle. A low velocity impact is not uncommon. For example, dropping of a tool on a composite structure during a routine inspection characterizes a low velocity impact incident, not to mention incidents during manufacturing, transportation, installation, and service. For armor-grade composite structures, low to high strain rate impact or blast is the primary criterion in structural design. Although both low and high velocity impacts are of concerns, a low velocity impact is more dangerous because it is often neglected by visual inspection. For example, after a low velocity impact on a laminated composite, only a small indentation may be seen on the impacted surface. However, significant damage may have been induced inside the laminate and on the back surface, which cannot be detected by naked eyes. As a result of the damage, the residual load carrying capacity of the structure may be considerably reduced, leading to premature and catastrophic structural failure. Therefore, the focus of this paper will be on low velocity impact.

Low velocity impact of composite structures (laminated, sandwich, grid stiffened) has been a topic of research interests for years allover the world. Many researchers have experimentally and theoretically investigated the low velocity impact response and residual strength of composite structures, including instrumented low velocity impact testing, analytical modeling based on modified Hertz contact law or conservation of energy, and finite element modeling using commercial software package like LS-DYNA. There is no short of supply of literatures in this research area. These studies have greatly enhanced the understanding of the impact behavior, damage, energy dissipation mechanism, and residual structural performance. As a result, more and more impact tolerance/resistance composite structures are being designed and manufactured with confidence.

In order to further increase the impact tolerance and/or resistance, more and more new and innovative composite materials and structures are being developed for more effectively absorbing impact energy. To better guide the new material/structure design and development, there is a need for reevaluating and revisiting the damage initiation and propagation, energy dissipation mechanisms, and rehabilitation technology.

Low Velocity Impact Damage

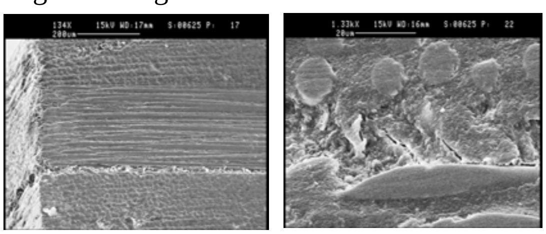
A low velocity impact induces various types of damages in fiber reinforced laminated composite structures. In addition to the visible indentation on the impacted surface and cracking on the back surface (Fig. 1 (a) and (b)), the most prevalent damage inside a laminated composite includes delamination, matrix cracking, fiber fracture, and fiber/matrix interfacial debonding; see Fig. 2. In a sandwich structure, a similar indentation can be identified on the impacted surface. On the back surface, however, the cracking may or may not be seen due to the energy absorption of the core (as a cushion layer). Inside the core, significant damage may be induced. The types of damages depend on the types of core used. For instance, if a syntactic foam core is used, damages may include crushing of the microballoons, matrix cracking, and microballoon/matrix interfacial debonding; see Fig. 3. For grid structures, the damage is similar to laminated composites in a smaller degree. The damage is more localized due to the elimination of materials mismatch in the ribs and the constraint of each rib section provided by the nodes. However, it has impact windows.



(a) Front surface Indentation

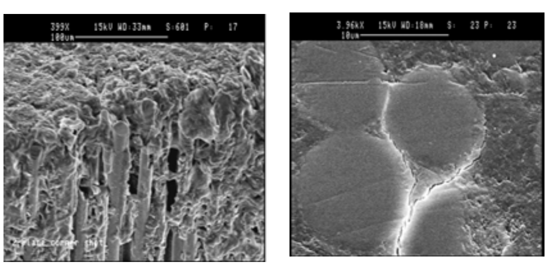
(b) Back surface cracking

Fig. 1 Damage on the front and back surfaces



Delamination

Matrix cracking



Fiber fracture

Interfacial debonding

Fig. 2 Damages inside a laminate

Energy Dissipation Mechanisms

In addition to the sound and heat produced, which contribute to dissipate impact energy in a negligible degree for a low velocity impact, there are two primary mechanisms for dissipating impact energy. One is energy transfer, and the other is energy absorption.

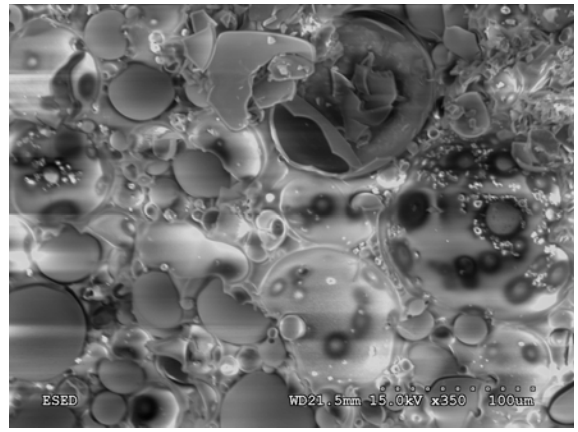


Fig. 3 Microballoon crushing and interfacial debonding

The first mechanism is energy transfer. In the event of a low velocity impact, the disturbance is transferred outward from the point of impact in the form of longitudinal wave and transverse wave. The predominant longitudinal tensile stress wave travels at the wave speed of disturbance. At the same time the transverse wave propagates at a velocity lower than the wave propagation speed of the material. Generally, as long as the impact velocity is smaller than the elastic wave propagation speed, this type of elastic wave propagation will always be seen. When the impact velocity is so high that the elastic wave cannot reach the boundary of the structure and is localized within a small area, it belongs to the category of high velocity impact. This is why a high velocity impact is a localized event and independent of boundary conditions, while a low velocity impact is a boundary dependent event.

With the propagation of elastic waves, the impact energy will be transferred to the affected materials and the materials up to the wave front will flow back towards the impact point, inducing kinetic energy and elastic strain energy in the target. These types of energy will be dissipated later by creating/propagating damage, vibrating and damping, and returning to the projectile. Because composite materials are light weight and the deflection during impact is small, the potential energy transferred to the target can be neglected.

The other mechanism is energy absorption. During an impact of a laminated composite or a grid stiffened composite, the energy is absorbed primarily by (1) indentation (plastic deformation), (2) delamination, (3) matrix cracking, (4) fiber fracture, and (5) fiber/matrix interfacial debonding. For a sandwich structure, in addition to the mechanisms for the laminated skins, a foam core serves to absorb energy through (1) densification, (2) matrix cracking, (3) microballoon crushing, and (4) interfacial debonding. For a core other than a foam core, for instance web core, truss core, 3-D integrated core, etc., other mechanisms also contribute to absorb impact energy. Regardless of the particular mechanisms, it is concluded that the energy is absorbed through damage and permanent deformation.

Description of the Impact Process

At the instant when the projectile contacts the target, the impact process starts. Figure 4 shows a typical load/velocity vs. deflection curve and Figure 5 shows a typical load/energy vs. time curve using the DynaTup 8250 HV machine. The impact process can be divided into three distinct stages; see Fig. 5.

Stage 1. It is seen that once the projectile contacts the target, the load applied to the target increases from zero until the maximum impact load is reached. The energy transfer between the projectile and the target is through the work done by the impact force. Up to the maximum impact force, the work done to the target is primarily used to accelerate the target (kinetic energy) and elastically deform the target (elastic strain energy). Only a small portion of impact energy is used to create invisible damage in the target, such as microcracks, microbuckling, and indentation. All the work done in this period is positive, as reflected by the energy-time curve, which shows a continuous increase in impact energy. With the increase of the impact load, the stress is increasing until the maximum load is achieved, where the stress is so high that macro damage is created. This indicates the end of Stage 1.

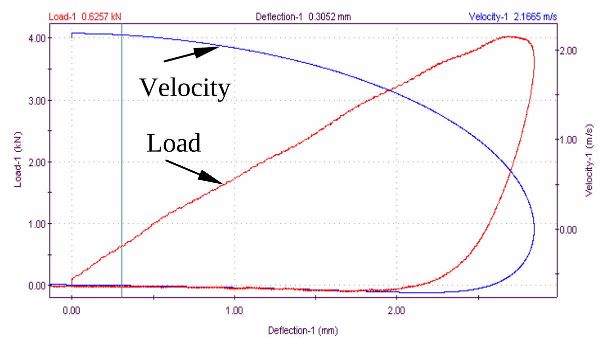


Fig. 4 Load/velocity vs. deflection

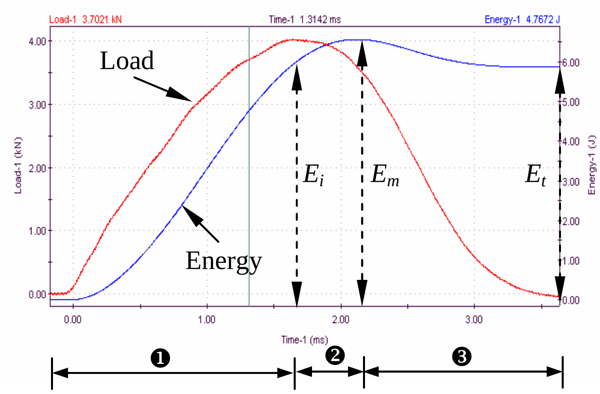


Fig. 5 Load/energy vs. time

Stage 2. When the stress comes to its maximum (corresponding to the maximum load), major damage initiates. Once the major damage is induced, the stiffness of the target is reduced, and the impact load starts to reduce. Due to the inertial of the target, it does not stop at the maximum load. Instead, it continues to deflect, with a continuously reducing contact (impact) load. Because the load is in the same direction as the deflection, the load continuously does positive work to the target. This means the impact energy is still in increasing, which is used to produce and propagate more damage. The target continues deflecting until it comes to the maximum deflection. Once the target comes to the maximum deflection, it stops (zero velocity), and the energy of the target comes to its maximum value. In this stage, the energy is primarily used to propagate the damage and only a small portion is used to increase the strain energy. Since the target stops at the maximum deflection, the kinetic energy is zero and all the elastic energy is in the form of strain energy.

Stage 3. After that, the target rebounds, the projectile is pushed back by the target. In this stage, the direction of the impact force and the direction of the displacement are opposite (negative velocity). The impact force does negative work to the target or does positive work to the projectile. A portion of the strain energy transfers back to the projectile. As a result, the energy of the target is in decreasing, so is the impact force and deflection, until separation of the projectile from the target (zero impact force). Depending on the nature of the target, the deflection may be fully recovered (to zero) or cannot be fully recovered, leading to plastic deformation.

At the end of Stage 3, i.e., when the projectile is separated from the target, the target still contains kinetic energy and strain energy (the velocity and the deflection are not zero). Based on the work-energy principle, the integration of the load-deflection curve (the work done to the target) is equal to the absorbed energy due to damage and plastic deformation plus the remaining kinetic energy and strain energy:

$$W = E_a + E_r \tag{1}$$

where W is the work done to the target, which is equal to the area covered by the load-deflection curve (also equal to the impact energy recorded by the impact machine E_t); E_a is the absorbed energy due to damage and plastic deformation; E_r is the residual elastic energy of the target (kinetic energy and strain energy). Obviously, the total absorbed energy E_t recorded by the impact machine is larger than the energy permanently absorbed by the target, E_a, i.e., through damage and plastic deformation.

Revisit Initiation Energy and Propagation Energy

Generally, Stage 1 is called damage initiation. The energy corresponding to the maximum impact load is termed as the initiation energy, E_i. Stages 2 and 3 are termed as damage propagation. The corresponding energy is called as propagation energy, E_p. In mathematical form, the propagation energy satisfies:

$$E_p = E_t - E_i \tag{2}$$

In some cases, for instance the structure has a very high strain energy at the end of Stage 2 (for high strength and high stiffness materials), it is found that $E_t < E_i$. This suggests that $E_p < 0$. Obviously, this is physically meaningless or wrong. In order to overcome this difficulty, this paper suggests that the energy increased at Stage 2 be used as the propagation energy:

$$E_p = E_m - E_i \tag{3}$$

where E_m is the maximum impact energy.

The rationality of this modification is that: (i) Stage 2 is the primary stage for damage creation and propagation. Therefore, the energy increment in Stage 2 is a reasonable estimation of the permanently absorbed energy. (ii) Since it is always true that $E_m \geq E_i$, it insures that $E_p \geq 0$. The difficulty of having negative energy is overcome. (iii) The results from both equations are consistence, i.e., if the E_p is small from Eq. (2), the E_p from Eq. (3) is also small, and *vice versa*.

It is noted that E_p is by no means the permanently absorbed energy because it contains a small portion of elastic energy; for the same reason, E_i is not fully elastic because it contains a small portion of permanently absorbed energy. Because the complexity of the problem, it is difficult to obtain the truly absorbed energy E_a.

Ideal Structure for Impact Tolerance

It is noted that a higher E_i almost always means a stronger and stiffer material, while a higher E_p means a weaker and tougher material. An ideal structure requires that it uses stronger, stiffer, tougher, and lighter material. This is difficult to achieve using a single material because some of the requirements are obviously contradictory. It is suggested that hybridization in both materials and structures scales may be a way out. This may be a direction for developing next generation of high performance and impact tolerance composite structures.

Rehabilitation Technology

Once impact damage is introduced into a composite structure, a proper repair and rehabilitation technology is required to regain the lost structural capacity and functionality. Field level repair generally requires an adhesively bonded approach to provide the load transfer and restore the design strength of the composite structure. Currently, two techniques are available for the repair, along with various types of repair materials. The two techniques are scarf repair and lap (single or double) repair. The repair materials include ambient environment curing material, which is cured at a room temperature, prepreg material, which is cured at an elevated temperature, and fast curing material by ultraviolet, visible light, and microwave. Each of the materials has merits and limitations. The ambient curing material is easy to use and does not require additional equipment besides a brush and a roller. However, it usually requires one to seven days for complete curing of the resin. Heat activated curing prepreg can reduce the repair time to several hours. However, these materials generally require freezer storage and have a limited shelf life. Heat and pressure are required to cure the adhesive and patch materials in order to obtain a uniform, nonporous adhesive layer. This leads to the following limitations. First, prepreg curing requires a curing temperature with a narrow tolerance. However, due to thermally complex structures, achieving curing temperatures within the required range is often difficult. Second, heating large areas using heat blankets requires large amounts of energy that can easily exceed available power sources. Third, for structures with complicated geometries, the required curing pressure is generally difficult to apply. Fast curing materials using the wet lay-up technology is gaining acceptance because the material can be cured within minutes. However, it needs additional curing sources, its uniformity is not as good as other curing methods, and its shrinkage is usually high.

Summary

This paper discussed the damages induced in fiber reinforced polymer composite structures by a low velocity impact. Focus is on the energy dissipation mechanisms and the understanding of the energy transfer and energy absorption during impact. The propagation energy is redefined to avoid possible negative values. The merits and limitations of the existing repair and rehabilitation materials are evaluated.

Acknowledgement

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LOW VELOCITY IMPACT RESPONSE OF A HYBRID SYNTACTIC FOAM

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Introduction

A core is the most crucial component in a composite sandwich structure. It takes care of separating and fixing the skin, carrying the transverse shear load, and providing other structural or functional duties such as impact resistance, radiation shielding, etc. In practice, various core materials have been used, such as foam core (balsa wood, polymeric foam, metallic foam, ceramic foam, syntactic foam, etc.), web core (truss core, honeycomb, corrugated core, 3-D integrated core, etc.), and foam filled web core (foam filled honeycomb and foam filled 3-D integrated core) [1,2]. Although the existing core materials have been very successful in carrying static and dynamic loads, there is considerable room left for further improvement in enhancing the specific energy absorption capacity because foreign object impact is becoming a major concern for most applications of composite sandwich structures. The purpose of this study is to develop a novel hybrid syntactic foam core for more effectively absorbing impact energy.

Microstructure Design

Syntactic foam – a light weight material with polymeric, ceramic, or metallic microballoons dispersed in a polymer matrix, is becoming more and more accepted in impact tolerant sandwich structures. The underlying principle for absorbing impact energy is that the microballoons will be deformed and crushed, the microballoon/matrix interface will be debonded, and the matrix will be cracked. The crushing of the microballoons and the creation of new surfaces serve to consume a considerable amount of impact energy. In order to further enhance the energy absorption capacity, more energy absorbing mechanisms must be introduced without significantly sacrificing strength. In this study, a novel microstructure is proposed and developed. This foam has a carefully designed microstructure with rubber coated microballoons dispersed in a nanoparticle and microfiber reinforced polymer matrix. Each component is designed to contribute to a desired property of the foam. The nanoparticles and microfibers serve to increase the strength and stiffness; the microballoons serve as a weight-reducing agent and filler; and the rubber coating serves as a structural layer to increase the toughness and the impact tolerance. This multi-phase material contains structures bridging over several length-scales, which would contribute to absorb and dissipate impact energy with minimal loss in strength.

Raw Materials

The resin system used was DER 332 epoxy with DEH 24 curing agent from DOW Chemicals. Other ingredients included microballoons (Q-cel 6048), milled micro glass fibers (Fiberglast), nanoclay (I28.E from Nanocor) and rubber latex (Rovene 4040 from Mallard Creek Polymers).

Specimen Preparation

To create the designed microstructure, the procedure for preparing the foam material started with coating the microballoons using the rubber latex while stirring and heating until the water was removed. The nanoparticles and microfibers were mixed with DER 332 using the ultrasonic mixer until uniformity. The curing agent was added to the DER 332 mixture followed by adding the rubber coated microballoons while stirring. Mixing was done continuously until uniformity. The mixture was then poured into an aluminum mold for curing. Once the molded slab was cured, it was cut into

304.8mm long, 50.8mm wide, and 15.2mm thick beam specimens. A total of four groups of specimens were prepared. Each group contained 12 identical specimens. The volume fraction of each group is given in Table 1. Six specimens from each group were wrapped using two layers of E-glass 7715 style plain woven fabric reinforced epoxy to fabricate sandwich beams.

Table 1 Volume fraction of each group (%)

Group No.	1	2	3	4
Epoxy	40	40	40	100
Rubber	-	-	10	-
Microballoon	60	55	45	-
Nanoclay	-	2.5	2.5	-
Microfiber	-	2.5	2.5	-

Experiment

Two types of tests were conducted. One was a low velocity impact test using the DynaTup 8250HV impactor with a hammer weight of 3.4kg and a velocity of 3m/s, and the other was a four-point bending test using the MTS 810 machine with a span length of 254mm and a loading rate of 4.1mm/min.

Results and Discussion

The impact test results of the pure core and sandwich specimens are given in Tables 2 and 3, respectively. The bending test results of the pure core, sandwich, and sandwich after impact, are summarized in Table 4. No residual bending strength is available for pure cores because they are significantly damaged and bending test cannot be conducted. From Table 2, the introduction of microballoons into the epoxy (Group 1) reduces the initiation energy and increases the propagation energy. This suggests that the microballoons reduces the strength of the epoxy and provides more microstructures for energy absorption. Addition of nanoclay and microfiber leads to increase in propagation energy, suggesting that nanoclay and microfiber serve to enhance the energy absorption capacity (Group 2). As expected, the addition of rubber to the mixture (Group 3) significantly increases the propagation energy, with a slight reduction in strength (initiation energy). The impact of sandwich structures in Table 3 follows a pattern similar to the pure cores. From Table 4, the sandwich construction significantly increases the bending strength of the core. After impact, the reduction in bending strength is the largest for the pure epoxy core (Group 4), followed by the Group 1 and Group 2 cores. The least reduction is found in the Group 3 core, i.e., with rubber addition. This strength retaining capacity with enhanced energy absorption suggests that the Group 3 core has a potential in advanced sandwich structures.

Table 2 Impact test results of pure core

Group No.	1	2	3	4
Initiation energy (J)	1.7	1.8	1.4	3.6
Propagation energy (J)	8.2	9.7	11.9	7.2

Table 3 Impact test results of sandwich

Group No.	1	2	3	4
Initiation energy (J)	9.3	8.1	6.5	12.5
Propagation energy (J)	4.0	5.3	6.8	0.8

Table 4 Bending test results

Group No.		Peak bending load (N)
1	Pure core	590.0
	Sandwich	4274.6
	Impacted sandwich	3762.5
2	Pure core	551.0
	Sandwich	4473.3
	Impacted sandwich	4054.2
3	Pure core	217.3
	Sandwich	4400.5
	Impacted sandwich	4236.2
4	Pure core	2153.8
	Sandwich	6464.4
	Impacted sandwich	5411.4

Acknowledgement

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A RUBBERIZED NANOCOMPOSITE FOAM CORE

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Introduction

Syntactic foams are light-weight composite materials consisting of hollow spheres embedded in a resin matrix. It is desired to further improve the toughness and impact resistance of these materials by adding other particles without a significant sacrifice of strength. Studies have shown improvements in the toughness of epoxies by adding particles in the nanometer range along with rubber particles [1]. An enhancement of damage tolerance was also noticed by the addition of micro-fibers to epoxy matrix systems [2].

In this study, a syntactic sandwich foam with hollow glass particles, crumb rubber particles, microfibers and nanoparticles in various compositions was proposed and tested. It is expected that the incorporation of different particles would help in improving the impact resistance and reducing the brittle nature of the epoxy matrix, and at the same time obtaining a light weight material.

Raw Materials

The major components constituting the foam material included the epoxy DER 332 and the hardener DEH 24 (DOW chemicals), Nanomer I.28E (Nanocor Inc.), 1.6-mm long Milled Glass Fibers (Fiberglast), Q-cel 6048 hollow glass particles (Potters Industries), and Crumb rubber (Rouse Polymerics).

Fabrication

Pure epoxy was prepared as the control specimen, which is named as batch 1. Three other batches of specimens were fabricated with 0%, 10% and 20% volume fractions of crumb rubber, respectively. The volume fractions of the epoxy, nanoclay and milled fibers were fixed at 40%, 1.6% and 0.8% respectively for these 3 batches. The detail of the volume fraction of each batch is summarized in Table 1. After curing, the foam slab was demolded, cut to beam specimens 304.8-mm long, 50.8-mm wide and 15.2-mm thick. Each batch contained 12 identical specimens.

Nine of these specimens were wrapped with 2 layers of E-glass 7715 plain woven fabric reinforced epoxy to prepare a sandwich structure, while the others were left unwrapped, to be used as core specimens.

Table 1. Volume fractions of each batch

Batch No.	1	2	3	4
Rubber	0	0	10	20
Glass beads	0	57.6	47.6	37.6

Testing and Results

The cured specimens were subjected to low velocity impact tests and four-point bending tests. Impact tests were conducted on both wrapped and unwrapped specimens at a velocity of 3m/s and a hammer weight of 3.4kg using a Dynatup 8250HV machine to determine the initiation and propagation energies. Further, the wrapped and unwrapped specimens were subjected to four-point bending tests to evaluate the residual strength. The impact test results of the core and sandwich specimens are summarized in Tables 2 and 3, respectively. Table 4 enumerates the bending strength for the core specimens of each batch. Residual strength of these specimens could not be obtained due to the fracture of the core specimens after impact testing. Table 5 summarizes the residual strength of the sandwich specimens.

Table 2. Impact Test Results of Core Specimens

Batch No.	Initiation Energy (J)	Propagation Energy (J)
1	12.93	0.37
2	3.11	1.62
3	6.43	2.31
4	7.20	2.63

Table 3. Impact Test Results of Sandwich Specimens

Batch No.	Initiation Energy (J)	Propagation Energy (J)
1	12.08	1.13
2	9.43	3.90
3	11.83	1.81
4	12.62	3.13

Table 4. Bending Strength Results of Core Specimens

Batch No.	Peak bending load (N)
1	2153.8
2	480.79
3	381.52
4	438.90

Table 5. Bending Strength Results of Sandwich Specimens

Batch No.	Peak bending load (N)	Residual peak bending load (N)
1	6464.43	5411.39
2	4473.30	4054.20
3	5849.80	5154.92
4	5730.90	4427.36

Results Discussion

From Table 2, the initiation energy and the propagation energy is the highest and lowest respectively for the neat resin. On the other hand, the addition of glass beads reduced the initiation energy, but at the same time more energy was absorbed through damage propagation. Further addition of rubber to the foam increased the initiation and propagation energies. A similar trend is found in the sandwich specimens from Table 3. This suggests that with the addition of crumb rubber, the resistance to crack initiation has improved and more energy has been absorbed through damage propagation.

From Table 4, the bending strength was the highest for the neat resin core specimen. On the other hand the bending strength decreased drastically with the addition of glass and rubber to the neat resin. Comparing Tables 4 and 5, adding a thin layer of fiber reinforced epoxy skin on the core significantly increased the bending strength of the foam core. From Table 5, the bending strength and residual strength is the highest for the neat resin specimen (Batch 1) followed by a decrease for Batch 2 specimen and then an increase from Batch 2 to Batch 3. This is followed by a decrease in the strength from Batch 3 to Batch 4.

It can be concluded that Batch 3 specimens absorbed more impact energy (Tables 2 and 3) and at the same time retained much of the strength after the impact tests (Table 5). It has a potential to be used in high performance sandwich structures.

Acknowledgements

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A NOVEL CEMENT BASED SYNTACTIC FOAM

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Introduction

Cellular cement is a lightweight material consisting of Portland cement paste or mortar with a homogeneous void or cell structure created by introducing air or gas in the form of small bubbles (usually 0.1 to 1.0 mm in diameter) during the mixing process [1,2]. Their unique set of properties makes them attractive as a foam core material for structural sandwich panels: they have moderate thermal insulation, high heat capacity, high stiffness, excellent fire resistance and low cost relative to polymer foams. For most sandwich structures, however, they require that the core be able to absorb a major amount of impact energy and have water tightness. Due to the brittleness of hardened cement paste and the open-cell structure, the current available cement foam is unable to absorb a sufficient amount of impact energy and to retain water tightness.

In this study, a novel cement based syntactic foam is proposed, developed, and tested. This foam is formed by dispersing microballoons into a modified cement paste. The cement paste is modified by adding rubber latex and by mixing with nanoclay particles and microfibers. This unique microstructure is carefully designed with each component being responsible for a certain structural/functional requirement. The microballoons are responsible for reducing the weight and retaining water tightness because of its closed-cell structure; the rubber latex is responsible for toughening the cement matrix and providing water for curing the cement; the nanoparticles and microfibers are responsible for increasing the strength. The materials selection, specimen fabrication and impact test results are presented in this paper.

Raw Materials

Primary constituents used in preparing the specimens are Type III Portland Cement (Lafarge Cement), Hollow Glass Spheres (Q-cel), Milled Micro Glass Fibers (Fiberglast), Nanoclay (I28.E from Nanocor) and Rubber latex (Rovene 4040 from Mallard Creek Polymers).

Specimens Preparation

Four groups of specimens were prepared. The details of the volume fraction used in each group are given in Table 1. The constituent materials were mixed, cast, compacted, finished, and cured in a wood mold. The cured slab was then cut using a diamond saw to 304.8mm long, 50.8mm wide and 15.2mm thick specimens. Each group contained 20 identical specimens. Twelve of the specimens from each group were then wrapped with 2 layers of E-glass 7715 style plain woven fabric reinforced epoxy to prepare sandwich beams. The resin system used was DER332 epoxy with DEH24 curing agent from DOW Chemicals.

Table 1. Volume fractions (%)

Group No.	1	2	3	4
Cement	10	15	20	100
Nanoclay	0.5	0.75	1	0
Glass fiber	0.11	0.165	0.22	0
Rubber	35.23	29.04	22.85	0
Water	4.43	13.79	23.15	0
Microballoons	49.33	40.66	32	0

Testing and Results

Two types of tests were conducted, one was a low velocity impact test and the other was a four-point bending test. Impact tests were conducted using the DynaTup 8250HV machine on both wrapped and unwrapped specimens with 2m/s, 3m/s and 4m/s velocity and a hammer weight of 3.4kg. The failure mode and the variations in initiation and propagation energies were recorded. Four-point bending test was also conducted on both wrapped and unwrapped specimens to determine the residual strength. Control specimens were also tested using the same four-point bending test fixture to determine the bending strength without impact damage. The impact test results of the core and sandwich specimens are summarized in Tables 2 and 3 and bending test results are given in Tables 4 and 5, respectively.

Table 2. Impact test results of pure core

Group No.	Initiation Energy (J)			Propagation Energy (J)		
	2m/s	3m/s	4m/s	2m/s	3m/s	4m/s
1	3.7	6.3	3.5	3.1	5.7	19.2
2	1.8	1.9	2.3	4.6	10.1	21.8
3	2.1	0.7	1	4.4	10.8	24.8
4	0.18	0.36	0.9	0.14	0.31	0.9

Table 3. Impact test results of sandwich

Group No.	Initiation Energy (J)			Propagation Energy (J)		
	2m/s	3m/s	4m/s	2m/s	3m/s	4m/s
1	5.1	9.9	10.5	1.1	2.1	14.2
2	5.6	9.5	11.9	0.6	1.6	13.5
3	5.9	7.8	11.7	0.3	4.3	13.7
4	3.7	3.3	5.0	1.9	9.7	19.0

Table 4 Bending test results of pure core

Group No.	Initial peak load (N)	Residual peak load (N)		
		2m/s	3m/s	4m/s
1	188	-	-	-
2	256	-	-	-
3	323	-	-	-
4	287	-	-	-

Table 5. Bending test results of sandwich

Group No.	Initial peak load (N)	Residual peak load (N)		
		2m/s	3m/s	4m/s
1	1912	1882	1837	1774
2	2515	2473	2318	2259
3	3178	3062	2707	2452
4	2914	1906	1087	1042

Results and Discussion

From Table 2 it can be seen that both the initiation energy and the propagation energy are the lowest for the pure cement core due to its brittleness. In particular, its propagation energy is so low that the cement core has no ability to absorb impact energy through damage propagation. Among the three rubberized foams, the initiation energy is the highest and the propagation energy is the lowest for the Group 1 specimens. This suggests that the higher the rubber content, the higher the resistance to damage initiation and damage propagation. From Table 3, it is seen that both the initiation energy and propagation energy for each group are close for the rubberized cores. The reason for this may be that the skin is primarily responsible for carrying the impact load. The core only plays a secondary role. The effect of the core on absorbing impact energy cannot be fully displayed. It is believed that, however, the effect will be "felt" as the impact energy increases. The cement core sandwich shows the highest propagation energy. This is not due to the energy absorption of the core; instead, it is due to the skins because it was observed that the projectile perforated both the top and bottom skins. Therefore, the energy absorbed is not by the cement core but by the skins. Comparing Table 4 with Table 5, it is seen that a thin composite skin significantly increased the peak load of the core. After a low velocity impact, all the pure core specimens were fractured and residual bending tests could not be conducted. For the sandwich specimens with rubberized core, it is seen that a significant amount of peak load has been retained after impact damage, in particular for Group 1 specimens. It is noted that, however, the foam peak load of the Group 3 is 1.73 times of that of Group 1. This ratio becomes about 1.38 after they are wrapped and impacted. This suggests that the Group 1 foam is more effective in serving as a sandwich core than the Group 3 foam. For the cement core sandwich, its residual peak load is significantly reduced, consistent with its small energy absorption capacity.

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EXPERIMENTAL STUDY OF COMPOSITE SANDWICH STRUCTURES WITH A GRID STIFFENED HYBRID CORE

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Introduction

Recently, various core materials have been used in composite sandwich structures, such as foam core (balsa wood, polymeric foam, metallic foam, ceramic foam, syntactic foam, etc.) [1-3], web core (truss core, honeycomb, corrugated core, 3-D integrated core, etc.) [4], and foam filled web core (foam filled honeycomb and foam filled 3-D integrated core) [5]. Since most composite sandwich structures are designed to be impact-tolerant, in particular for armor-grade structures, it is desired that more energy be dissipated during impact with minimal sacrifice in load carrying capacity. In a sandwich structure, it is the core that is primarily responsible for absorbing the impact energy. In order to further enhance the energy absorption with a minimal penalty in residual strength, a new sandwich core is proposed and developed in this study. The skeleton of the core was made of a continuous fiber reinforced 2-D orthogrid that was filled with a novel syntactic foam in the bay area. The objective of this paper is to present the impact and residual strength test results of the novel sandwich structure.

Specimen preparation

Three types of sandwich structures were fabricated: (a) foam sandwich (syntactic foam as a core), (b) grid sandwich (orthogrid as a core) and (c) hybrid sandwich (orthogrids filled with syntactic foam as a core).

The facing of the sandwich coupons was made of E-glass fiber reinforced ultraviolet curing vinyl ester. The cured facing thickness was 0.76 mm. The fiber used for the grids was E-glass rovings; the resin was the same vinyl ester. The grid structure was a 2-D orthogrid, with the rib thickness of 12.7mm and width of 2.5mm. The interlacing orthogrids formed 25.4mm-by-25.4mm square bays. The syntactic foam was manufactured by mixing 50% by volume of Q-cel microballoons (average size 50μm and bulk density 0.14g/cm^3) with the same vinyl ester. Flat panels with a dimension of 381mm × 381mm × 12.7mm were fabricated using the hand lay-up technology. After curing, the sandwich panels were cut into 165.1mm × 50.8mm × 12.7mm beams for testing.

Experiments

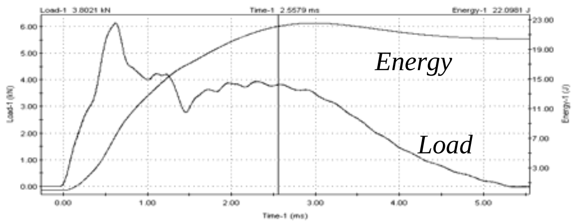
Two types of testing, low velocity impact test using DynaTup 8250HV with a velocity of 4m/s and a hammer weight of 33N, and residual bending strength test using a four-point bending fixture with a span length of 152.4mm on an QTEST150 machine, were conducted on the three types of sandwich structures. The loading rate was 5.08mm/min.

Table 1 Summary of test results

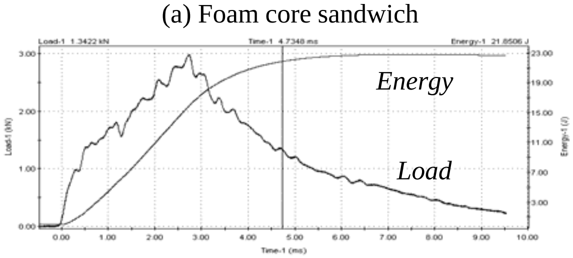
Types of specimens		Foam core	Grid core	Hybrid core
Peak impact load (KN)		6.0	3.0	9.0
Initiation energy (J)		7.5	16.0	18.0
Propagation energy (J)		13.0	6.8	1.5
Maximum bending load (N)	Before impact	5,500	3,100	13,000
	After impact	3,500	2,100	10,520
	Reduction (%)	36.3	9.7	19.0

Results and discussion

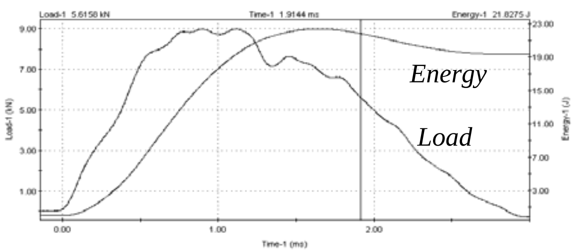
The test results are summarized in Table 1. Typical load-time and energy-time responses for the three types of specimens are shown in Fig. 1. From Table 1, the peak load of the hybrid core sandwich (9KN) is significantly higher than that of the foam core sandwich (6KN) and the grid core sandwich (3KN). This suggests a higher load carrying capacity of the hybrid core sandwich. The initiation energy is the highest and the propagation energy is the lowest for the hybrid core sandwich. Therefore, the hybrid core dissipates energy primarily through damage initiation. Once the damage is initiated, it is localized without wide-spread propagation (small propagation energy). Figure 2 shows the back face of impact-damaged specimens. It is observed that the hybrid core sandwich has the



(a) Foam core sandwich



(b) Grid core sandwich



(c) Hybrid core sandwich

Fig. 1: Performance of representative sandwich structures due to impact

least damage in the back surface because the damage has been localized to the bay which is under direct impact. The least damage insures that the hybrid core sandwich has a higher residual strength. It is evident from Table 1 that a low velocity impact (4m/s) reduced the bending strength of the foam core sandwich by 36.3%; grid core sandwich by 9.7%; and hybrid core sandwich by 19.0%. This suggests that the presence of the orthogrid reduces the damage propagation in the foam. It is noted that the desired composite action observed in these experiments is constructive which leads to significantly higher bending strength for the hybrid core sandwich than the sum of the bending strength of the two reference sandwiches (13,000N versus 5,500N + 3,100N = 8,600N before impact and 10,520N versus 3,500N + 2,100N = 5,600N after impact).

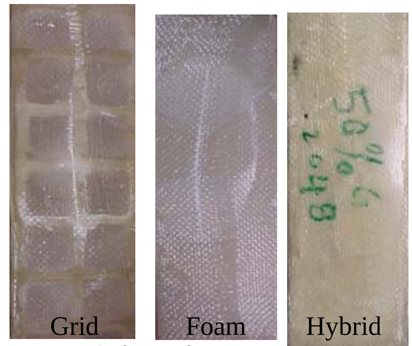


Fig. 2: Back face of specimens after impact

Summary

In summary, the enhancement in the impact energy dissipation and residual bending strength in the proposed hybrid core sandwich can be mainly contributed to the orthogrid, the foam, and the composite action between the FRP ribs and the filled syntactic foam.

Acknowledgement

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